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ESTUARY ECHOES: UNRAVELING RESEARCH TRENDS WITH BIBLIOMETRIC ANALYSIS IN SRI LANKA

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ABSTRACT

Estuaries can be found all throughout Sri Lanka's coasts, but the kinds of research that have been done on them, their relative importance, and the trends in those studies have not been systematically examined until now. Therefore, the aim of the present review is to undertake a bibliometric analysis of estuaries in the context of Sri Lanka, comprising trends in publication, most-cited articles, influential authors, collaborating nations, prominent institutions, journal types, keyword co-occurrence, and bibliographic coupling in the field. Articles on Sri Lankan estuary research published in the Web of Science (WoS) database between 1987 and 2023 were analyzed using bibliometric techniques and visual mapping. This study examined 58 papers in total, Visualization of Similarities (VOS) viewer was used to analyze data. 1987 to 2011 had one or two publications per year, however the positive quadratic coefficient (0.0074) indicates an accelerating growth trend in publications over time. Many studies have been conducted focusing on the Negombo estuary. Notably, the majority of articles focused on water quality studies. Further, fisheries, mangroves, and environmental-related research have also been undertaken equally in this regard. However, the findings emphasize the necessity of integrating spatial information techniques, geological and geographical data, coastal sediment dynamics, tourism, and further studies on sea-level rise in estuaries. Many studies have focused mainly on the southern and western parts of the estuaries. The Northern Coastal Zone's estuaries remain largely unexplored. High-security zones surrounding the estuaries, particularly in the coastal regions to the north and east, restrict researchers' freedom to conduct certain research. Fewer studies have been conducted, yet those that have are detailed. Therefore, the review indicates that future research should consider an integrated, multidisciplinary, and holistic ecosystem approach to Sri Lanka's estuaries.

Keywords: Estuary, bibliometric analysis, VOS similarities, ecological, Web of Science

INTRODUCTION

Estuaries are transitional locations where both fresh and saltwater mix on a global scale, assembling rich environments that support unique biodiversity and ecological processes as well as providing significant social, cultural, and economic values (Chilton *et al*., 2021; Elliott *et al*., 2015). Coastal estuaries and lagoons, which represent 13 % of the world's coastal zones, are among the most dynamic wetlands (Bjorn Kjerfve, 1994). Almost 60 % of the world's most populous cities are located on or near estuaries, which proportionately characterize one of the Earth's richest natural regions (Abdul Maulud *et al*., 2022; Bruner de Miranda *et al*., 2017). The estuaries and their adjacent landscapes are a mosaic of various ecological communities that provide many benefits to coastal ecology and the economy of that area (Barbier *et al*., 2011; Gray *et al*., 2018). Estuaries have a wide range of functions because of the strong physical and chemical gradients they create and the availability of nutrients from nearby catchments (Thrush *et al*., 2013; Toriman *et al*., 2012). In addition, estuaries serve many significant fin and shellfish as spawning and nursery grounds (Beck *et al*., 2001; Amarasinghe, 1997; Miththapala, 2013; Samarakoon & Saman, 2012). Therefore, the study of estuaries and their management is a very important task for livelihood, coastal environmental monitoring, and protection (Van & Binh, 2008).

Estuarine geomorphology fundamentally governs ecological structure and function by controlling hydrodynamic regimes, sediment distribution, and habitat heterogeneity, which in turn regulate primary productivity, nutrient cycling, and biodiversity patterns (Chilton *et al*., 2021). Variations in channel morphology, tidal prism, and sedimentary processes create a mosaic of habitats such as mudflats, salt marshes, and mangroves that support diverse biological communities and provide critical ecosystem services, including carbon sequestration and nursery grounds for fisheries (Day *et al*., 2012; Elliott & McLusky, 2002). Moreover, the geomorphological evolution of estuaries influences their resilience to anthropogenic pressures and climate-driven changes, such as sea-level rise and altered sediment supply, thereby directly affecting ecological stability and conservation outcomes (Barbier *et al*., 2011; Kirwan & Megonigal, 2013). Consequently, integrating geomorphological perspectives into estuarine studies is essential for understanding ecosystem dynamics and for developing effective, science-based management and conservation strategies.

In terms of livelihood and food production, estuaries and lagoons play a significant part in the everyday lives of coastal residents in Sri Lanka (Sarathchandra *et al*., 2018). Several scientific studies have been conducted in Sri Lanka's estuaries (Table 1). The island's topography includes highlands in the south-central region (Fig. 1), which range in altitude from 300 to around 2500 meters, and extensive lowland plains that extend to the coastal areas (Rathnayake *et al*., 2011; Reuter *et al*., 2020). The physiography is best summarized as a central mountain range, the Central highlands, rising in a succession of layers or ramparts from a low (Fig. 1a,b), flat plain that surrounds it on all sides and extends to the sea (Cooray, 1984). Therefore, as the central part of the country is high and the coastal areas are low, this has paved the way for the formation of 103 rivers and the possibility of estuaries including lagoons along the coastal area around the island (Fig. 1c). Due to the Central high land series and seasonal circumstances, the climatic zones of Sri Lanka and their conditions are shifted. All of the aforementioned elements have an impact on the rivers and their estuaries around the island.

Fig. 1(*a*): Elevation of Sri Lanka derived from the ASTER GDEM (*b*) Central Highlands and its surroundings ramparts in 3D view (*c*) Location of major rivers and their inlets in the estuaries and lagoons in the coastal line.

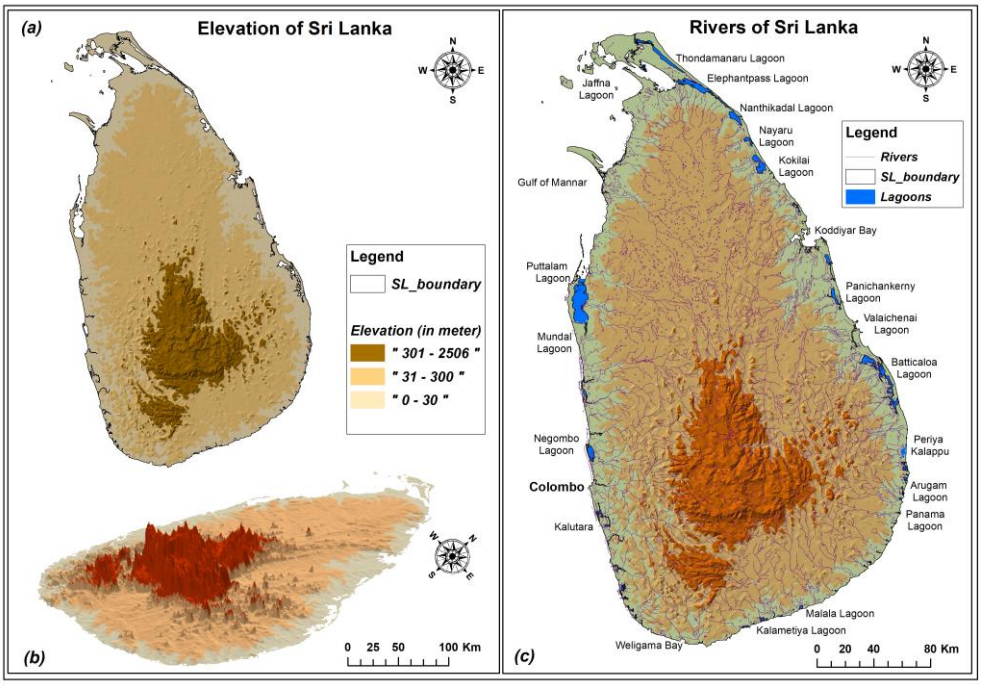


Table 1: Examples of subjects explored in Sri Lankan literature about estuaries between 1987 and 2023.

Article Title	Document Type	Reference
Territorial use rights in fisheries (TURFS) in Sri Lanka - Case studies on Jakottu – fisheries in the Madu Ganga estuary and Kattudel- fishery in the Negombo lagoon	Proceedings paper	(Atapattu, 1987)
Water exchange in a hypersaline tropical estuary, the Puttalam lagoon, Sri Lanka	Research Article	(Arulananthan *et al*., 1995)
Investigation of the Negombo estuary (Sri Lanka) Brush Park fishery, with an emphasis on community-based management	Research Article	(Amarasinghe *et al*., 2002)
Anthropogenic impacts recorded in the sediments of Lunawa, a small tropical estuary, Sri Lanka	Research Article	(Ratnayake *et al*., 2005)
Integration of multisource data for Chlorophyll –A monitoring in Negombo estuary, Sri Lanka	Proceedings Paper	(Dahanayaka *et al*., 2011)

Chloride contamination in construction aggregates due to periodic saline water intrusion: a case study in the Kaluganga river estuary, Sri Lanka	Research Article	(Ratnayake *et al*., 2013)
Participatory Geographic Information Systems for environmental zoning plan: Case study of the Madu Ganga estuary, Sri Lanka	Book Chapter	(Alagan & Aladuwaka, 2013)
Spatial variations in recent ostracode assemblages and bottom environments in Trincomalee Bay, northeast coast of Sri Lanka	Research Article	(Iwatani *et al*., 2014)
Atmospheric carbon removal capacity of a mangrove ecosystem in a micro-tidal basin estuary in Sri Lanka	Research Article	(Perera & Amarasinghe, 2016)
Mangrove diversity across salinity gradient in Negombo estuary-Sri Lanka	Book Chapter	(Chandrasekara *et al.*, 2016)
Chemical composition and possible sources of suspended particulate matter in the peripheral environments of Batticaloa lagoon, Sri Lanka	Research Article	(Adikaram *et al*., 2017)
Morphological correlates with diet of fish assemblages in Brush Park fisheries of tropical estuaries	Research Article	(Gammanpila *et al*., 2017)
Impacts of mangrove density on surface sediment accretion, below ground biomass and biogeochemistry in Puttalam lagoon, Sri Lanka	Research Article	(Phillips *et al*., 2017a)
Potential impact of predicted sea level rise on carbon sink function of mangrove ecosystems with special reference to Negombo estuary, Sri Lanka	Research Article	(Perera *et al*., 2018)
Carbon sequestration capacity of mangrove soils in micro tidal estuaries and lagoons: A case study from Sri Lanka	Research Article	(Perera & Amarasinghe, 2019)
Probabilistic application of an integrated catchment-estuary-coastal system model to assess the evolution of inlet-interrupted coasts over the 21st century	Research Article	(Bamunawala, Dastgheib, Ranasinghe, van der Spek, Maskey, Murray, Barnard, *et al*., 2020)
Nature-based tourism development in coastal wetlands of Sri Lanka: An importance-performance analysis at Madu Ganga mangrove estuary	Research Article	(Marasinghe *et al.*, 2021a)
Eutrophication and Hypoxia in tropical Negombo lagoon, Sri Lanka	Research Article	(Hsieh *et al*., 2021)
Assessment of marine turtle nesting habitats from Tangalle to the Kumbukkan Oya estuary in South-eastern Sri Lanka	Research Article	(Perera *et al.*, 2022)
Fish diversity and assemblage in the Batticaloa lagoon, Sri Lanka	Research Article	(Harris *et al.*, 2023)

Coastal estuaries are important coastal habitats in Sri Lanka, which is surrounded by sea on all four sides. However, no detailed and systematic studies of Sri Lanka's estuarine ecosystems have been conducted to date (Sarathchandra *et al*., 2021; Wickramasingha *et al*., 2025), necessitating such study reviews to identify research trends and gaps. To our knowledge, this work is the first to do a bibliometric analysis of all articles relating to Sri Lanka's estuaries that were included in WoS during the period from 1987 to 2023. The objective of this study is to systematically analyze the existing literature on estuaries in the context of Sri Lanka, covering trends in publication, most-cited articles, influential authors, collaborating nations, prominent institutions, journal types, keyword co-occurrence, and bibliographic coupling in the field. As a result, this bibliometric study provides a visual structure, an overview, and trends related to estuaries and associated information. Therefore, this article may provide new knowledge for researchers in planning their future studies. The following is the structure of this research article: The introduction section factually integrates traditional literature reviews on estuaries, Sri Lankan estuaries, and prior literature, with a personal viewpoint and interpretation. Data collection using VOSviewer is described in the materials and methods section. Section three provides a thorough examination of research outcomes and their classifications. The section reveals trends in publication, most-cited articles, influential authors, collaborating nations, prominent institutions in the field, journal types, keyword co-occurrence, and bibliographic coupling. Eventually, the discussion identified knowledge gaps, and the conclusion summarizes very relevant findings and suggests possibilities for further research, emphasizing the work's extensive applicability.

MATERIALS AND METHODS

Bibliometric analysis

The bibliometric analysis is a study of scholarly papers to explore for trends and patterns (Zamzuri, 2021). Bibliometrics allows for the mapping and proliferation of knowledge in a certain field of study, displaying linkages between major publications, authors, institutions, topics, and other aspects of the subject (José de Oliveira *et al*., 2019; Liao *et al*., 2018). Performance analysis and scientific mapping are two key areas for bibliometric data analysis. Science mapping shows the structure and dynamics of research disciplines, whereas performance analysis investigates the research and publishing performance of people and organizations (Donthu *et al*., 2021; Dzikowski, 2018; Montalván-Burbano *et al*., 2020). Through identifying linkages between academic journal citations, bibliometric studies can support readers in gaining a good perspective on current research progress and future research goals (Chen *et al*., 2017). In this research, two bibliometric approaches were integrated and applied: performance analysis and scientific mapping. In general, the bibliometric measures included the author's publications, name of the organization, interested countries, and journal articles, citations, co-citations, bibliographic couplings, and keyword co-occurrences are the most commonly evaluated bibliometric displays (Donthu *et al*., 2021; Fang *et al*., 2018; Garrigos-Simon *et al*., 2018; Lima & Bonetti, 2020; Mulet-Forteza *et al*., 2018, 2019; Singh *et al*., 2020; Singh & Dhir, 2019). When two papers are referenced in the same paper, they are counted as co-citations. It is possible for two articles to be bibliographically linked when the third article is cited in both of them. A study of keyword co-occurrences identifies which terms appear most frequently in the literature (Singh *et al*., 2020). Bibliographic coupling is defined as when two researchers cite the same third publication (Oh & Lee, 2020; Singh *et al*., 2020).

Data source and analysis

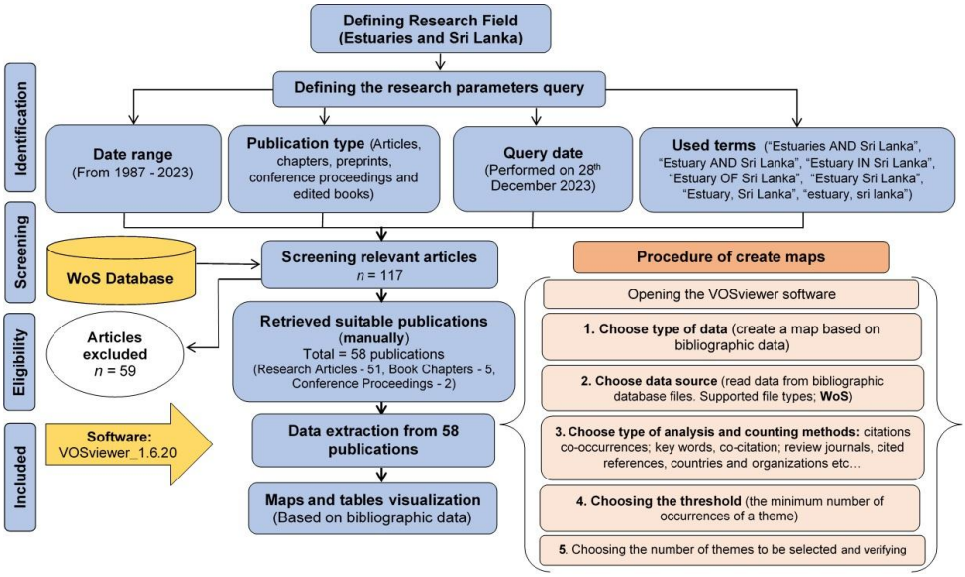
Among the most commonly visited consistent databases, Web of Science (WoS), Scopus, and Google Scholar are the most popular, as they cover a wide spectrum of scientific information (Lima & Bonetti, 2020). The most optimal method would be to combine all of the databases into one. It is difficult to merge and filter data for integrated analysis since each database has a distinct structure. As a result, when undertaking a bibliometric study, using a single database is the best approach (Donthu *et al*., 2021). However, it should be noted that a single database will never be able to include all of the data available; as a result, this technique will always have limitation. In this study, scientific data on estuaries study of Sri Lanka was gathered from documents indexed in the WoS database. The WoS database, maintained by the Institute for Scientific Information (ISI), is an influential, interdisciplinary, quarterly, full-text collection of data that is widespread used for exploring scientific literature and citation data (Chen *et al*., 2017; Liu *et al*., 2019). It has a more accurate and consistent record of success when screening literature for numerous contexts (Mohamad *et al*., 2023). As the most powerful research engine, the WoS provides accurate publication and citation data that may be used to confidently access and analyse research. The WoS provides a more complete record of index journals, books, and conferences of the social sciences, natural sciences, arts and humanities, and other fields than other databases such as Scopus. As a result, data for this research was synthesized from the WoS database (Chen *et al*., 2014; Chen *et al*., 2017; Liu *et al*., 2019).

The analytical data for this study was acquired from the WoS core collection database in December 2023. To access the database, users must first obtain an institutional subscription. During the data obtaining stages, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Page *et al*., 2021) was utilized to ensure transparency in the inclusion and exclusion criteria used for selecting appropriate articles to carry out mapping. As a consequence, the authors of this study employed the following keywords in the WoS database's main search box to discover all articles: "Estuaries AND Sri Lanka", “Estuary AND Sri Lanka”, “Estuary IN Sri Lanka”, “Estuary of Sri Lanka”, “Estuary Sri Lanka”, “Estuary, Sri Lanka”, “estuary, sri lanka”. The title, abstract, author keywords, and keywords plus were all included in the topic search engine. By focusing on materials published in the English language, the search conditions were narrowed down even more. However, when screening and inclusion the related publications, the following aspects also were taken into consideration: (A) direct research of Sri Lankan estuaries have been considered; (B) if the study topic is not directly related to estuaries but is revealed to be about the estuaries inside it, then that sort of article has been examined. Such publications have also been considered; (C) during in the study of Sri Lanka's lagoons, the estuaries were also surveyed. Publications of this nature have also been taken into account. After screening the dataset, the authors removed articles that had irrelevant information. All suitable documents have been exported to a tab-delimited file (text file) with full descriptions and cited sources. When downloading a tab-delimited Text (.txt) file, the Excel (.xls) version of the same file was also downloaded for convenient reference. According to the above-mentioned criteria, the downloaded publication datasets were then carefully checked for errors by two reviewers. A total of 117 documents were found by the search engine (including articles, conference proceedings papers, and book chapters). However, 59 documents were eliminated from the search as it was irrelevant. Since the "Estuary and Sri Lanka" database is accessible from 1987 (first publication), the required documents were gathered between 1987 and 2023. At the end, 58 eligible publications were considered for this study. The downloaded tab-delimited file was used for full descriptions and cited sources. Fig. 2 shows the PRISMA flow diagram of the methodology.

VOSviewer

VOSviewer is free software with an interactive and user-friendly interface. The findings of the studies were displayed using the VOSviewer version 1.6.20 (Yuan & Sun, 2023). It was selected because it can handle massive data sets, provides a variety of analysis and study choices, and generates coherent images that help with data evaluation (Yuan & Sun, 2023). Because we exclusively used data from the WoS database, the chances of data duplication and omission have been quite low (Pathmanandakumar *et al*., 2021). In addition, the research findings were supported by an analysis of the data on the WoS website. The WoS database and VOSviewer software were used to adjust both full and fractional counts for this study. Circle sizes correspond to an object's weight. The distance of the items reveals the strength of the connections.

Fig. 2: PRISMA flow diagram of the systematic study.



RESULTS

Over the last 35 years, estuary researchers have explored and characterised the research trends, number of studies, and study areas on Sri Lankan estuaries. The findings of the bibliometric review begin with general statistics in this study. The second part of the results explore on how far Sri Lankan estuary studies have grown and its current growth. This review concludes by looking at how the country's publications are linked together. The study revealed 51 articles, 2 conference papers, and 5 book chapters. It consisted of 58 papers written by 201 authors affiliated with 86 institutions in 22 countries. The review emphasizes that 21 countries, in addition to Sri Lanka, have expressed interest in studying more about Sri Lanka's coastal estuaries.

Publication trend of estuary studies in Sri Lanka from the literatures

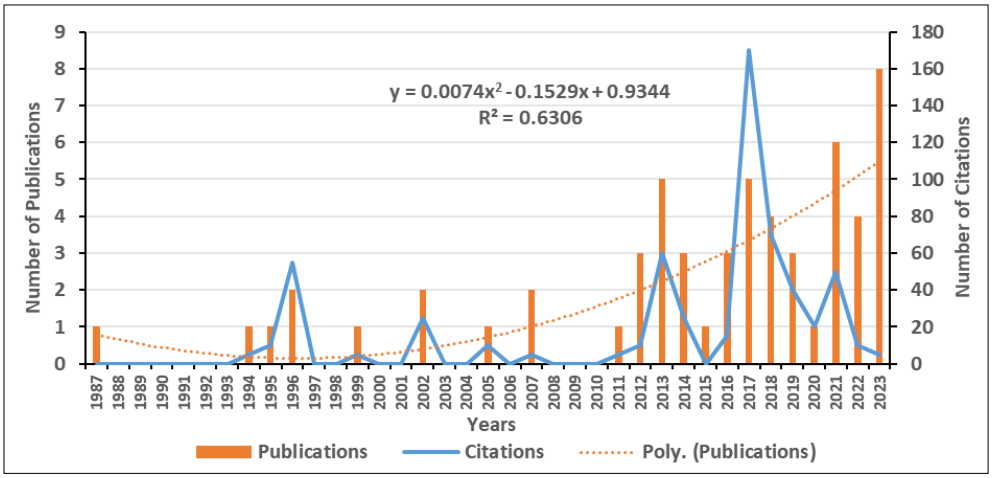
The effectiveness and competence of a researcher reflects upon the number of articles that have been published. The number of articles publicly released each year is also a vital index of the development of a specific area of research, and it may be used to analyse its progress (Pathmanandakumar *et al*., 2021; Rana, 2020). In accordance with the information gathered, the first article, titled "Territorial use rights in fisheries (TURFS) in Sri Lanka - Case studies on Jakottu – fisheries in the Madu Ganga Estuary and Kattudel- fishery in the Negombo Lagoon" was published in the conference proceeding of the Food and Agricultural Organization - FAO/Japan expert consultation on the development of community - based coastal fishery management systems for Asia and the Pacific by Atapattu, AR (Atapattu, 1987) and was published by FAO, United Nations. The study focused on the fisheries field of the west coast of Sri Lanka. Similarly, the last article published from the extracted database, with the title "Blue carbon storage in a tropical coastal estuary: insights for conservation priorities" was published jointly (Suwandhahannadi *et al*., 2023) with foreign collaborations. The study aimed to measure the amounts of organic carbon stored in seagrass meadows within a tropical estuary on Sri Lanka's southern coast. It also pointed out the importance of seagrass conservation, particularly when it comes to managing lagoons effectively in order to meet the Sustainable Development Goals. Maps showing the distribution of seagrass for 2022 were created using Landsat 9 (OLI/TIRS) data, and the results were confirmed using field observation. Samples of soil and vegetation were collected from eight sites that represented the Rekawa Lagoon. This research has provided light on how to preserve these important ecosystems and emphasized the need for enhanced management.

In general, Fig. 3 portrays an upwards trend in estuary-related research over the preceding 36 years, from 1987 to 2023. However, the period from 1987 to 2023 was characterized by fluctuations in the number of WoS articles on Sri Lanka's estuarine research. The absence of any articles on estuaries over a long period of time from 1988 to 1993 highlights a very downward trend on this subject. Apart from this, there were no publications discovered in the WoS core database during 1997 and 1998, 2000 and 2001, 2003 and 2004, 2006, and 2008 to 2010 under the estuary studies in Sri Lanka. It is possible that this is due to the fact that no researchers were interested in the topic. However, regular publishing on these topics commenced in 2011, with one publication alone. In the years after, with some changes in 2017, 2021, and 2023, the number of publications has continued to increase, with some fluctuation. The most number of documents on Sri Lanka's estuary research were published in 2023 (8 publications), followed by 2021 (6 publications), 2017 and 2013 (5 publications per year). Despite the fact that the research production varies from one year to the next, there has been an upward movement in the research output between 2013 and 2023. This situation highlights the increased level of attention among researchers regarding this theme of estuary. Increasing coastal environmental impacts and human interventions on estuaries, can be attributed to the increase in such research outputs (Khaniya *et al*., 2021). It is significant to remember that, as of 15th of December 2023, eight research papers were published. It is possible that the number might increase by the end of the year. Although its publication numbers were low at the time of the first publications in WoS (1987), the increasing numbers of publications thereafter has shown a progress in the related study.

The amount of citations for papers about Sri Lanka's estuaries between 1987 and 2023 was also observed. Resulting, no research published between this years had more than 20 citations. Citation counts for published articles peaked in 2017 with a record of 172 citations. Some published works also had no citations at this time (Fig. 3). Citations for articles that were published after 2017 have gradually decreased. It may be possible that those published articles were not under open access to future researchers to use in their researches. In addition

to that, the positive quadratic coefficient (0.0074) indicates an accelerating growth trend in publications over time. Further, this trend displays a second-order polynomial distribution with the 63 % of variability explanation capacity, as denoted by the R^2 value. This condition may change in the future and a further increase in its numbers.

Fig. 3: Published articles and citations by years (1987-2023).



The most cited articles and influential authors

Citation records will be expected to characterize an article's relevance to the field in which it was published (Fang *et al*., 2018; Lima & Bonetti, 2020; Pathmanandakumar *et al*., 2021). The publications with the highest number of citations are often regarded as milestones because of their innovative contributions (Chen *et al*., 2012). Table 2 demonstrates the amount of citations for the top ten most referenced publications on the studies of estuaries of Sri Lanka between 1997 and 2023. Among all the studies published, Kodikara et al., and their publication entitled "Have mangrove restoration worked? An in-depth study in Sri Lanka" is the most widely referenced in relation to Sri Lanka's mangroves however, Sri Lanka's overall estuaries were covered in this research (Kodikara *et al*., 2017). It was published in Restoration Ecology, which is published by Wiley, in 2017, and it has acquired an overall total of 115 citations so far. This research directly studied on the mangrove restorations program in Sri Lanka, however, the survey included all of Sri Lanka's estuaries and lagoons. In this study, around 200–220 acres of mangrove restoration were found to be effective. During monitoring, 9 out of the 23 study locations revealed no surviving plants in the estuaries and lagoons. Among the locations investigated in this study, namely the Kalpitiya, Pambala, and Negombo estuaries and lagoons, had a percentage of survival of more than 50 %. Survival rates were shown to be significantly correlated with a variety of soil factors, with the exception of soil pH.

The title of the second most cited paper is "Utilization of mangroves and sea grasses by fishes in the Negombo Estuary, Sri Lanka". Forty four research papers have been cited this article since it was published in the journal of Marine Biology in 1996 (Pinto & Punchihewa, 1996a) and seventh in terms of citations per year (1.57). After two years of sampling, 10287 fishes belonging to 62 species (39 families) were gathered from the mangroves and sea grasses of the Negombo Estuary, which was the focus of the study. Sixteen species were caught exclusively from mangroves, six species were caught exclusively from sea grasses,

and forty species were caught from both. Ultimately, the results of the study suggested that the interaction of juvenile fishes with mangroves or sea grasses may not be required in estuaries with minimal tidal variations. The title of the third-most-cited publication is Middle to late Holocene environmental changes in the depositional system of the tropical brackish Bolgoda Lake, coastal southwest Sri Lanka. This work was highly scientific and technical and published in the journal of Palaeogeography. Palaeoclimatology. Palaeoecology (PALEO) in 2017 and received 34 citations (Ratnayake *et al*., 2017). The Algae productivity, enrichment of nutrients and alkane ratios were examined in this study. In this study, the authors have considered Bolgoda Lake as one of the largest river-dominant brackish estuaries in Sri Lanka. The study emphasizes the high primary production of the tropical aquatic and terrestrial environment leads the organic carbon levels in estuaries and lagoons to fluctuate quickly in response to changes in the environment. The study investigated into the environmental and geomorphological changes that occurred over the Holocene, as well as the depositional settings, variations in sea level, and paleoclimatic characters of the Holocene sediments in the Bolgoda Basin.

Table 2: Top ten cited research articles from 1987 to 2023.

Authors	Title	Publication Year	Citations	Average per Year
(Kodikara *et al*., 2017)	Have mangrove restoration projects worked? An in-depth study in Sri Lanka	2017	115	16.42
(Pinto & Punchihewa, 1996a)	Utilization of mangroves and seagrasses by fishes in the Negombo estuary, Sri Lanka	1996	44	1.57
(Ratnayake *et al*., 2017)	Middle to late Holocene environmental changes in the depositional system of the tropical brackish Bolgoda Lake, coastal southwest Sri Lanka	2017	34	4.85
(Perera & Amarasinghe, 2019)	Carbon sequestration capacity of mangrove soils in micro tidal estuaries and lagoons: A case study from Sri Lanka	2019	27	5.40
(Bellio & Kingsford, 2013)	Alteration of wetland hydrology in coastal lagoons: Implications for shorebird conservation and wetland restoration at a Ramsar site in Sri Lanka	2013	26	2.36
(Perera *et al*., 2018)	Potential impact of predicted sea level rise on carbon sink function of mangrove ecosystems with special reference to Negombo estuary, Sri Lanka	2018	25	4.16
(Amarasinghe *et al.*, 2002)	Investigation of the Negombo estuary (Sri Lanka) brush park fishery, with an emphasis on community-based management	2002	24	0.89
(Ranasinghe *et al*., 2013)	Mid-Late Holocene coastal environmental changes in southeastern Sri Lanka: New evidence for sea level variations in southern Bay of Bengal	2013	20	1.81
(Ratnayake *et al*., 2018)	Seasonal and tidal influence for water quality changes in coastal Bolgoda Lake system, Sri Lanka	2018	20	0.95
(Marasinghe *et al*., 2021b)	Nature-based tourism development in coastal wetlands of Sri Lanka: An Importance-Performance analysis at Maduganga Mangrove Estuary	2021	19	6.3
(Duong *et al*., 2018)	Assessing climate change impacts on the stability of small tidal inlets: Part 2-Data rich environments	2018	19	3.1

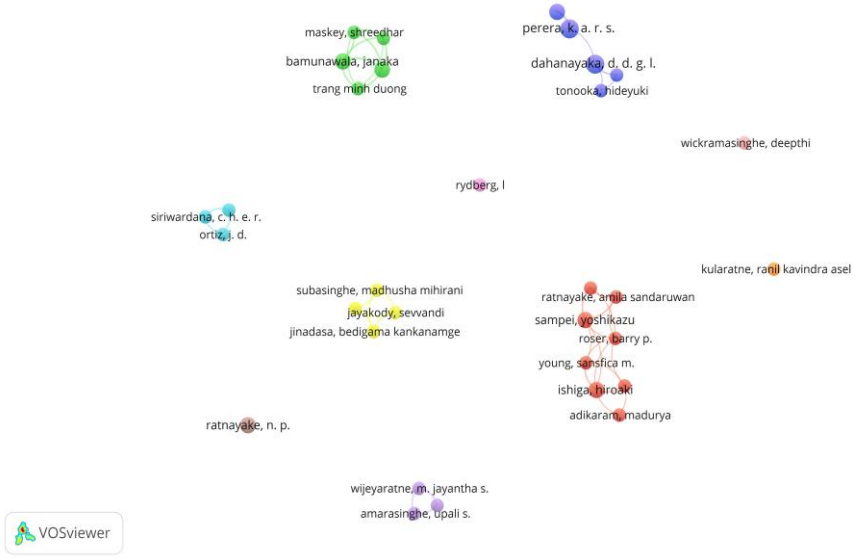
Table 3 shows the top ten most prominent researchers in Sri Lanka's estuary and related fields, as evaluated by papers published and citations. On the topic of estuary studies in general, 201 authors have contributed to the existing of knowledge. Based on the details that were gathered, Ratnayake Nalin Prasanna has the top ranking with 74 citations for his total of six publications on Sri Lanka's estuaries, while Perera K.A.R.S has written four total articles and has received 60 citations. He is second in the top ten citation list. In the meantime, Amarasinghe and Sampei both are at the third rank in the list with three research papers and 60 citations. Ranasinghe Roshanka and Bamunawala Janaka have the same number of articles on the subject (3 articles each) and their citations are also equal (43 each). Those who had two articles (Ratnayake Amila Sandaruwan) in the very first 10 articles, on the other hand, received more citations than those who had three articles, and their citations seemed to be 54. It is an interesting to note that six of the top ten researchers are from the Netherlands (2) and Japan (4).

Table 3: The top ten authors by publications and citations regarding the estuaries of Sri Lanka.

Authors	No of Documents	No of Citations	Institution Affiliation	Country
Ratnayake Nalin Prasanna	6	74	Department of Earth Resources Engineering, Faculty of Engineering, University of Moratuwa	Sri Lanka
Perera K.A.R.S	4	60	Department of Botany, The Open University of Sri Lanka, Nawala, Nugegoda	Sri Lanka
Amarasinghe M.D	3	60	Department of Botany, University of Kelaniya	Sri Lanka
Sampei Yoshikazu	3	60	Department of Geoscience, Faculty of Science and Engineering, Shimane University	Japan
Bamunawala Janaka	3	43	Department of Water Science & Engineering, IHE Delft	The Netherlands
Ranasinghe Roshanka	3	43	Department of Water Science & Engineering, IHE Delft	The Netherlands
Ishiga Hiroaki	3	16	Department of Geoscience, Shimane University	Japan
Ratnayake Amila Sandaruwan	2	54	Department of Geoscience, Faculty of Science and Engineering, Shimane University	Japan
Barry P. Roser	2	41	Department of Geoscience, Faculty of Science and Engineering, Shimane University	Japan
Siriwardana, C.H.E.R	2	34	Geological Survey and Mines Bureau, Sri Lanka	Sri Lanka
Wijesundara, D.T.D.S	2	34	Geological Survey and Mines Bureau, Sri Lanka	Sri Lanka

Fig. 4 displays the academic collaboration network between authors. Ishiga Hiroaki and Sampei Yoshikazu (shown in red) collaborated with Pitawala Amarasooriya, Ratnayake Amila Sandaruwan, Ratnayake Nalin Prasanna, Roser Barry P, Young Sansfica M and exposed concern in Geochemistry of sediments in three sectors of Trincomalee Bay, Sri Lanka. Further, they were interested in the study of Holocene environmental changes in the depositional system in the Bolgoda Lake of southwest Sri Lanka (Ratnayake *et al*., 2017; Young *et al*., 2014) in the cluster one. This map depicts the equal level of collaboration between Perera and Dahanayaka in cluster two (shown in blue). It has been disclosed that authors participating in studies together with them include Amarasinghe, Wijeyaratne, and Tonooka Hideyuki. Their researches also focused on the ability of mangrove ecosystems in Sri Lankan micro-tidal estuaries and lagoons to remove atmospheric carbon dioxide and sequester carbon from soils (Perera & Amarasinghe, 2016b, 2019a).

Fig. 4: The academic collaboration network of the 32 academics with a minimum 2 number of publications.



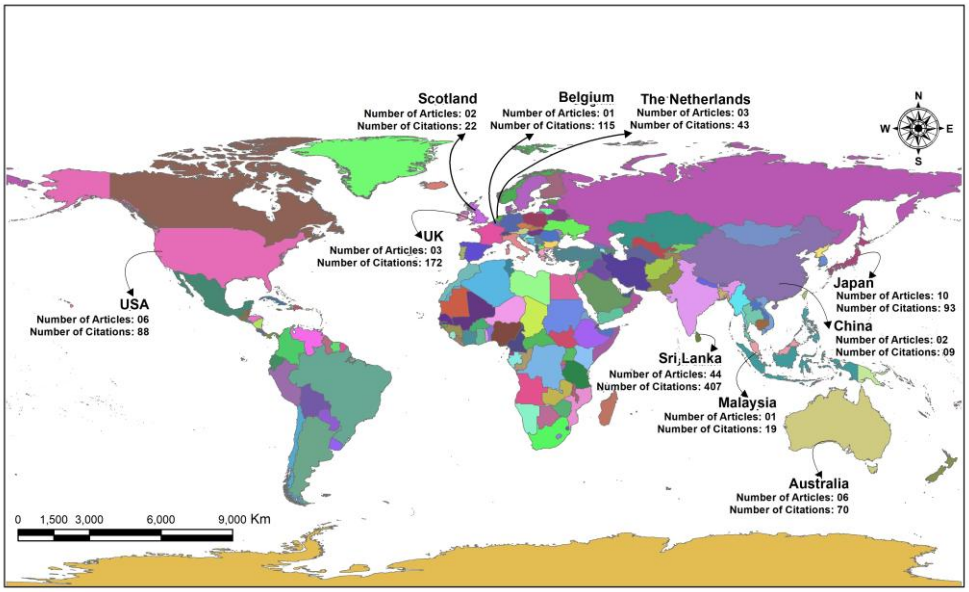
Janaka Bamunawala and Roshanka Ranasinghe (shown in green) have shown more interest in academic collaboration than others (Van der Spek. A.D, Maskey Shreedhar, Trang Ming Duong) in the cluster three. They were interested in assessing future coastline change in the tidal inlets through complexity modelling. Further, their collaborative study focused on the holistic modeling approach in the inlet-interrupted coastlines and probabilistic application in the integrated catchment-estuary-coastal system model to assess the inlet-interrupted coasts (Bamunawala *et al*., 2018; Bamunawala, Dastgheib, Ranasinghe, van der Spek, Maskey, Murray, Barnard, *et al*., 2020; Bamunawala, Dastgheib, Ranasinghe, van der Spek, Maskey, Murray, Duong, *et al*., 2020). In the cluster four (shown in yellow), Jinadasa Bedigama Kankanamge Kolitha Kamal have worked collaboratively with Subasinghe Madhusha Mihirani, Jayakody Sevvandi, Navarathne Ayanthi and their principal concern was with discovering the seasonal variations in the total lipid content and fatty acid composition were studied in Sri Lanka. In this study, wild and cultured populations of Crassostrea madrasensis

were considered in Gangewadiya in Kala-Oya estuary and in cultured populations in the Puttalam lagoon in Sri Lanka over a 13 month period (Subasinghe *et al*., 2019). It has also been found that some authors' collaborative efforts consist of only two or three people. However, Fig. 4, highlights the absence and characterization of some collaboration conditions for some article authors, whilst others have been involved in collaborative researchers with many affiliates.

Significant contribution of countries and institutions on Sri Lankan estuaries

The contributions of significant countries and institutions were evaluated in this section based on the authors' affiliations. Between 1987 and 2023, a total of 22 countries/territories and 86 institutions/organizations contributed to studies related to estuary in Sri Lanka. Despite the fact that this study is focused on Sri Lanka, it has been discovered that many different nations are interested in the related studies of the country. Fig. 5 displays the top ten nations that have had the greatest influence on the researches. Sri Lanka has been listed in the top with the 44 documents with 407 citations. Japan and the United States of America (USA) were the second and third largest interested countries about Sri Lankan estuaries respectively. However, the countries such as Australia, The United Kingdom (UK), Netherlands, Belgium, China and Malaysia are also reported to be interested in the subject. The amount of publications and citations in the WoS core collection indicated which country was the most productive in a certain study field at the time (Dzikowski, 2018). Sri Lanka, Japan, and the USA are the countries with the closest international corporate linkages on the study of estuaries. Even though Sri Lanka represents to be in the South Asian region, it is important to note that study on Sri Lankan estuaries is of considerable interest to nations outside of the region.

Fig. 5: The ten most productive and interested countries/territories on Sri Lankan estuary research.



From 1987 to 2023, statistics from the ten most significant institutes in estuary related studies are listed in Table 4. Among Sri Lanka's most productive institutions, the University of Kelaniya is the most productive, with the most publications (10 articles and 100 citations), followed by the University of Ruhuna (7 articles and 147 citations), National Aquatic Resources and Research and Development Authority (NARA) (7 articles), University of Moratuwa, Shimane University, University of Peradeniya and the University of Colombo (6 articles each). Several organizations, including the University of Twente in the Netherlands, Deltares in the Netherlands, the Open University of Sri Lanka, Uva Wellassa University, also have published articles in this regard as a result of these studies. Through the use of VOSviewer, co-authorship analysis was also used to explore academic collaboration across a variety of different organizations (Table 4). A co-authorship criterion was set at two documents and citations per organization. Out of 86 organizations, 11 fulfilled the bare requirement. Based on the criteria, there were 14 items (nodes), 5 clusters, and 19 links with a total strength of 32 among the academic cooperation networks.

Table 4: Information of the ten most influential institutions on Sri Lankan estuarine related studies.

Institution/Organization	Articles	Citations
University of Kelaniya, Sri Lanka	10	100
University of Ruhuna, Sri Lanka	7	147
NARA, Sri Lanka	7	25
University of Moratuwa, Sri Lanka	6	84
Shimane University, Japan	6	80
University of Peradeniya, Sri Lanka	6	32
University of Colombo, Sri Lanka	6	10
Open University, Sri Lanka	5	60
Uva Wellassa University, Sri Lanka	4	37
University of Twente, The Netherlands	3	43
Deltares, The Netherlands	3	43

Shimane University of Japan, University of Twente of the Netherlands, and Deltares, the Netherlands are the most active institutions in international academic collaboration on studies relating to estuaries of Sri Lanka. The findings indicate that institutions located outside of Sri Lanka have been more engaged in international collaboration on Sri Lankan coastal estuary research than those institutions within the country.

Analysis of different journals

Between 1987 and 2023, 49 journals published articles on estuary related of Sri Lanka. The top ten most popular journals are shown in Table 5. “Regional Studies in Marine Science” (3) was the most popular journal, followed by “Fisheries Management and Ecology” (2), “Frontiers in Marine Science” (2). The journal "Regional Studies in Marine Science” has produced three articles however, the journal "Restoration Ecology" only published a single article, but it was the most referred journal, with a total of 115 citations during the period. As well as another article has been published in the journal of “Marine Biology” and gained 44 citations. The impact factor of a journal will be used to evaluate its relative importance in the field. Compared to journals with lower impact factor values, journals with higher impact factor values were regarded as more prominent in the area (Chen *et al*., 2017; Liu *et al.*,

2019). "Ocean & Coastal Management" has the greatest impact factor (4.6) among the top ten most prolific journals, followed by "Frontiers in Marine Science" (3.7) and "Restoration Ecology" (3.2). When it comes to this group of journals, a high impact factor does not appear to be associated with a high ranking because a journal with the highest impact factor did not get the greatest number of manuscripts. Journals having a high impact factor, on the other hand, did not have a large number of citations. Also, Palaeogeography Palaeoclimatology Palaeoecology has the highest h-index (171), followed by Environmental Earth Science (141). One can see that 31 % of the articles (out of 58) pertaining to estuary studies were published in the top ten journals in these above categories, which demonstrates the importance of these journals in these sectors.

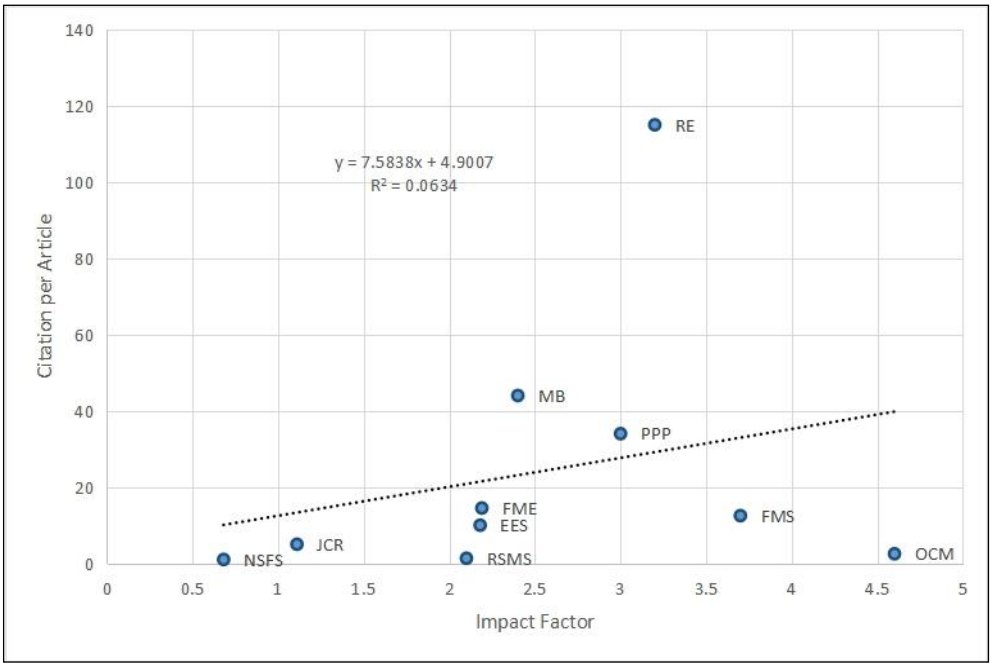
Considering central tendency and disparity, the top ten journals displayed a mean Impact Factor of 2.51 (+/- 1.15 SD) and a mean h-index of 91.1 (+/- 46.8 SD). While these 10 journals represent 31% of the total journals published on Sri Lankan estuaries, highlighting their key role in the field. The column of citation per article provides a normalized metric that is easier to compare across different journals. It states some journals have a massive influence despite having a low volume of articles in the study. Restoration Ecology recorded high with 115 citations per article, interpreting this journal only contributed one article to the dataset, that specific article is a highly influential work in Sri Lankan estuary studies. Journal of the National Science Foundation of Sri Lanka is currently lower compared to others in the list.

Table 5: The top ten refereed journals in terms of number of articles and citations published on Sri Lankan estuaries.

Journal	Total No of Articles	Total Citations	Impact Factor (IF) in 2023	h-index	Citation per Article
Regional Studies in Marine Science (RSMS)	3	4	2.1	31	1.33
Fisheries Management and Ecology (FME)	2	29	2.19	62	14.5
Frontiers in Marine Science (FMS)	2	25	3.7	85	12.5
Environmental Earth Science (EES)	2	20	2.180	141	10
Journal of Coastal Research (JCR)	2	10	1.11	99	5
Ocean & Coastal Management (OCM)	2	5	4.6	98	2.5
Journal of the National Science Foundation of Sri Lanka (JNSFS)	2	2	0.682	23	1
Restoration Ecology (RE)	1	115	3.2	111	115
Marine Biology (MB)	1	44	2.4	129	44
Palaeogeography Palaeoclimatology Palaeoecology (PPP)	1	34	3.0	171	34

To statistically interpret the relationship between journal prestige and regional research impact, a linear regression analysis was performed with scatter plot, depicted in Fig. 6. The scatter plot of Impact Factor versus Citations per Article revealed a coefficient of determination of 0.0634. The low R^2 indicates that global Impact Factor is not a strong predictor of citation frequency for studies related to Sri Lankan estuaries. Specifically, Restoration Ecology and Marine Biology appear as high-impact outliers, suggesting that specialized niche relevance drives citations more than general impact metrics.

Fig. 6: The scatter plot of Impact Factor versus Citations per Article on Sri Lankan estuary related journals.



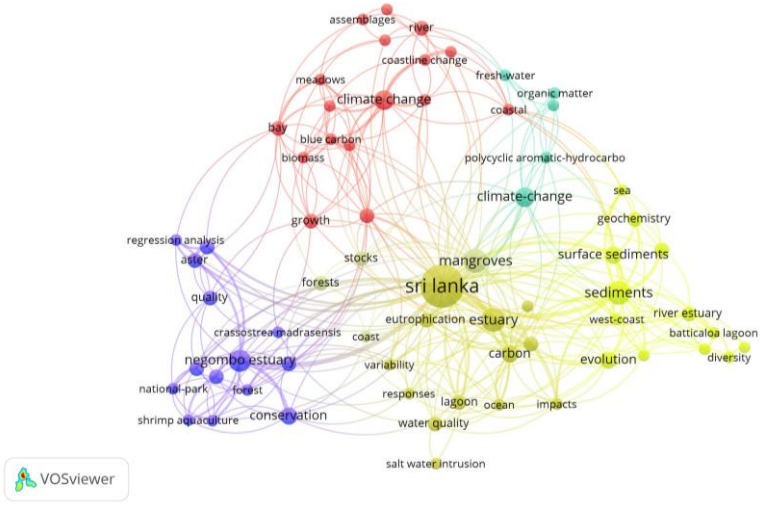
Co-occurrence all keyword analysis

The most often used keywords by scientists and researchers in the field of estuary studies serve as a guidance to their research goals and interests (Zhang *et al*., 2019). Keyword co-occurrence analysis could be used to detect latest study areas and research themes in a given subject since keywords indicate the precise content of the article (Mulet-Forteza *et al*., 2018; Singh *et al*., 2020; Singh & Dhir, 2019). In this study, all keywords are used purely as a way to identify the most relevant research subjects in the estuary related studies of Sri Lanka. As shown in Fig. 7(a), a network of co-occurrence all keywords has been constructed via VOSviewer, which is represented by 66 keywords, chosen from among a total of 421 occurrences of keywords, that each achieve a minimum of two occurrences of a keyword. "Sri Lanka," "mangroves," "sediments," "estuary," "Negombo estuary," "climate change," "carbon," "surface sediments" "evolution," "conservation," "organic-carbon," "eutrophication" were among the top ten keywords used by authors conducting estuarine related research in Sri Lanka between 1987 and 2023. Keyword vicinity and colour reflect greater similarities than keywords that are far apart from one another and of a different colour (Lima & Bonetti, 2020; Rana, 2020). The diagram shows seven clusters with 23 nodes, each of which is represented by a different colour.

Except the keyword of "Sri Lanka", the terms "climate change", "Negombo estuary", and "sediments" which were used more than five times each in all of the studied publications, are shown in Fig. 7(a). The key word of "climate change" was most often reported word in the cluster one (shown in red). In cluster two, the term "Negombo estuary" has emerged as the most often used keyword (highlighted in blue). A number of studies have been carried out in the Negombo estuary such as mangrove and sea grasses utilization, Chlorophyll-A

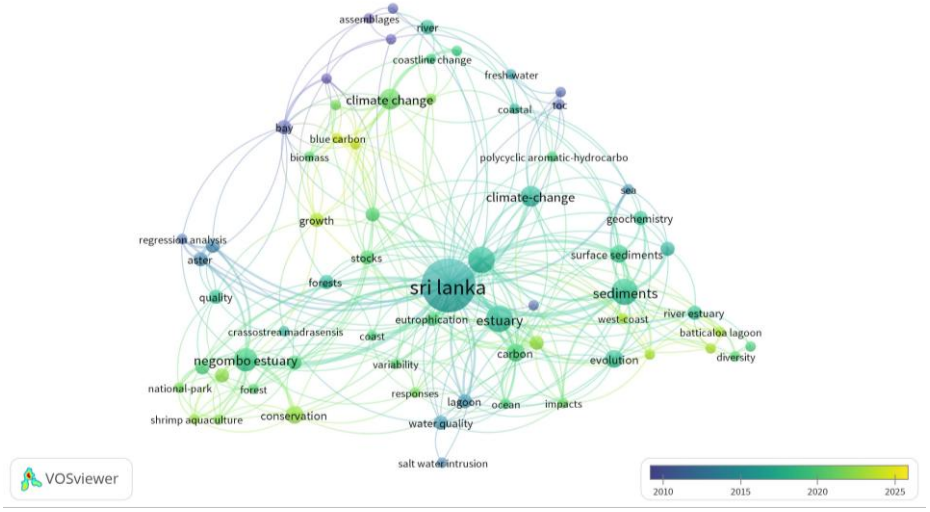
monitoring, and tidal choking and bed friction. “Sediments” and “surface sediments” are depicted as the key terms in the third cluster (shown in yellow).

Fig. 7a: Co-occurrence all keywords.



Furthermore, Fig. 7(b) illustrates through colour how the key words have emerged as significant themes in Sri Lankan estuary studies over time. Studying “salt water intrusion” and “organic matter”, “meadows”, “chlorophyll-a”, “mangroves” and “eutrophication” these things were major themes in estuary research from 2010 to 2019 periods. But the research theme trend has been changed to study about “climate change” and “coastline change impacts”, “surface sediments” and “blue carbon” and conservation studies on estuaries in recent years. It indicates that scholars are releasing their journal articles based on the contemporary needs of the country.

Fig. 7b: Co-occurrence all keywords trends by years.

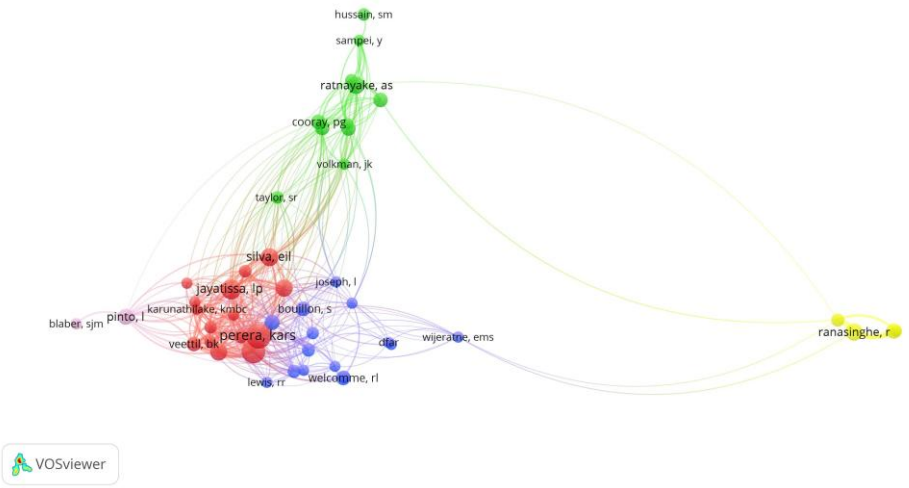


Co-citation analysis

Co-citation analysis of cited-authors

Co-citation techniques have been used to study authors and publications. When two previous articles are mentioned in a subsequent article, it is known as co-citation (Mulet-Forteza *et al*., 2018; Oh & Lee, 2020; Singh *et al*., 2020). Using co-citation analysis, researchers can comprehend how area develops. In this way, it can be a great tool in the knowledge of a subject's structure (Pathmanandakumar *et al*., 2021). To illustrate a subject's conceptual structure, it is possible to use it. Furthermore, co-citation research gives a valuable insights on the field of knowledge. The first co-citation study concentrated on the authors who have been cited. Cited authors in the co-citation analysis is depicted in Fig 8. It was determined that an author must have at least five citations. Out of the total of 1934 authors, 48 authors achieved the minimum threshold.

Fig. 8: Co-citation network comprising 48 authors who had reached the threshold for having at least five citations.



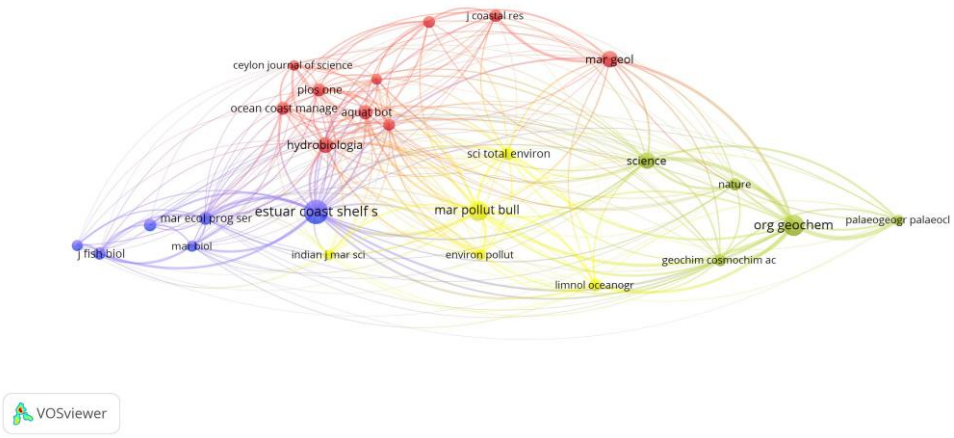
The network of referenced authors is comprised of five clusters, 47 nodes, and 382 linkages, with a total link strength of 2378. The first cluster, shown by red, has 15 authors; the second cluster, represented by blue, contains also 15 authors; and the third and fourth clusters, represented by green and yellow, have 11 and 04 authors, respectively. However, the core cluster in red contains the most referenced authors: Perera, K.A.R.S (23 citations), Amarasinghe, M.D (21 citations), and Jeyatissa, L.P (15 citations). This cluster was focused on the Carbon removal and sequestration capacity of a mangrove ecosystems in the micro tidal estuaries and lagoons of Sri Lanka (Perera & Amarasinghe, 2016, 2019). The second cluster (blue) is represented by Alongi, D.M (9 citations) Bouillon, S and Welcomme, R.L (8 citations each), Dahanayaka, D.D.G.L (6 citations). The authors' studies in this cluster mainly was focused on the monitoring of the Eutrophication and Chlorophyll conditions in the estuaries (Dahanayaka *et al.*, 2012). The third cluster is represented by the authors Ratnayake, A. S. (11 citations), Ratnayake, N. P. (8 citations), Cooray, P.G. and Katupotha. J (8 citations each). The authors in this cluster investigated the effect of seasonal and tidal

variations on water quality changes, as well as Holocene environmental changes in the depositional system. (Ratnayake *et al*., 2017, 2018). The fourth cluster (yellow) is represented by Ranasinghe, R (11 citations) and Syvitski, J.P.M (9 citations) and further two more authors. The main author has focused on holistic modelling approach to forecast the evolution of inlets and coast line complexity modelling in this cluster. The last cluster's (shown in pink colour) authors (Pinto, I and Blaber, S.J.M) focused on fishes' utilization of mangroves and sea grasses in estuaries and near-shore environments of estuaries (Blaber *et al*., 2000; Pinto & Punchihewa, 1996a). According to the Co-citation of authors' findings, they are continually interested about related subjects, and their publications are focused on it.

Co-citation review of cited sources (journals)

The co-citation study has also focused on the sources that have been cited. The co-citation cited sources (journal) review was used to ascertain the areas in which research is cited (Montalván-Burbano *et al*., 2021). A total of 26 journals were identified out of 1396 sources that fulfilled the minimum citation requirement of 12 citations per source, as seen in Fig. 9. The network of co-citation cited sources consists of 4 clusters, 248 links, and a total strength of 4878. First cluster, represented by the colour red, consists of 10 journals, which include Marine Geology (28 citations), Hydrobiologia (27 citations), Aquatic Botany (22 citations), Ocean & Coastal Management (19 citations), PLOS ONE (18 citations), Journal of Coastal Research (16 citations), Journal of Environmental Management and Nature Climate Change (15 citations each). Forest Ecology and Management and Ceylon Journal of Science (12 citations each). The leading cited journal and its publications in this cluster are concerned with the climate change impacts on the stability of small tidal inlets (Duong *et al*., 2018).

Fig. 9: The co-citation network of the 26 cited sources (journals) that reached the criterion of a minimum number of citations of a source of 12.



The second cluster, which is in blue, contains 6 journals, represented by Estuarine Coastal and Shelf Science (62 citations), Marine Ecology Progress Series (18 citations), Journal of

Fish Biology (17 citations), Fisheries Research (16 citations), Environmental Biology of Fishes and Marine Biology (13 citations each). Therefore, the journal of Estuarine Coastal and Shelf Science was the most cited in the cluster regarding the estuary studies. Five journals each are contained in the third (yellow) and fourth (green) clusters. In the third cluster, however, the top journal in the group was the Journal of Marine Pollution Bulletin, with 40 citations. Organic Geochemistry journal is also growing in importance as a highly referenced journal in the fourth cluster with 46 citations. Consequently, among the co-citation journals in the study, Estuarine Coastal and Shelf Science, Organic Geochemistry, and Marine Pollution Bulletin have obtained the top three rankings, apart from cluster-wise.

Bibliographic Coupling

The number of similar references between two publications is known as the bibliographic coupling. As subject clusters are generated in bibliographic coupling, depending on the cited articles, it is possible to make current and specialized articles more accessible (Donthu *et al*., 2021). By doing a bibliographic coupling analysis with the unit of analysis being "author," a visual analysis of the bibliographic coupling of authors is generated. The minimal number of publications and citations for each author was determined at two and thirty five, respectively. Consequently, out of the 201 authors, only 9 met the minimal requirements. With four documents and 190 link strength, Perera K.A.R.S leading the list, followed by Amarasinghe. M.D and Sampei Yoshikazu. The results show that Amarasinghe and Sampei have 440 link strength and have received three documents. Following the aforementioned authors, Ratnayake Nalin Prasanna and Ratnayake, Amila Sandaruwan are found at the third rank with two articles and 437 total link strengths. Two clusters were observed in this analysis. The first cluster was chaired by Sampei and includes three more authors (Ratnayake Nalin Prasanna and Ratnayake, Amila Sandaruwan and Roser Barry, P). Followed by another cluster which is made up of two authors only (Perera and Amarasinghe) and coordinated by both authors.

DISCUSSIONS

According to the findings of this paper, a detailed bibliometric analysis of research pertaining to the study of Sri Lanka's estuary was carried out by evaluating 58 publications from the WoS core collection database. Based on bibliometric measures, it offers a summary of the surge in the number of articles, the most cited papers, the most prominent authors, institutions, and collaborating nations in the field. While estuaries are essential to Sri Lanka's tourism, fisheries, and coastal biodiversity, a trend in number of WoS indexed articles reveals a deficiency in yearly publications about the country's estuary when compare with other fields of study. The analysis shows that the fluctuations in the number of articles published between 1987 and 2023 were noticeable. In some years the number of article publication has been found to be zero. However, from 1987 to 2011, the publication was one or two article per year and slightly higher after 2016. Therefore, in order to protect the long-term sustainability of its advancements, scholars in the field must dedicate themselves to increasing the volume of research and publications related to this subject. However, the study's findings show that interest in the Sri Lankan estuary is increasing over preceding the past few years. The fact that the number of publications on this subject has been increasing gradually recently is encouraging.

Between 1987 and 2023, the top ten most cited articles on the research of Sri Lanka's estuaries were also checked. On the list, (Kodikara *et al*., 2017) scored in the first rank, and

their publication was on mangrove restoration projects in Sri Lanka (Table 2). Themes such as mangrove studies, environmental changes, water quality, climate change impacts, and Brush Park fishing research largely dominated in the top 10 publications, with mangrove studies being the most popular. The study reveals that the majority of the researches have been done in the estuaries in Sri Lanka's western and southern coastal zones. Particularly in the Negombo estuary, where more than 15 studies have been carried out. Many studies have been conducted in that area, particularly those pertaining to mangroves and fisheries. The estuary's major economic activity is fishing. On the other hand, a number of studies on the Negombo Estuary have to be conducted due to growing water pollution, sedimentation, the loss of mangroves and sea grasses, and reducing water area (Dahanayaka, 2023). Furthermore, it is located in a wet zone may be also the main cause of this; as mangrove diversity is thought to be controlled by climatic conditions, the area is likely to exhibit higher mangrove density and diversity (Arulnayagam *et al*., 2021; Kathiresan & Bingham, 2001). This situation has been found suitable for detailed studies of mangrove and fisheries. These contexts might have been pertinent to many researches on fisheries and mangroves.

According to the findings of this study, a number of organizations and nations were interested in doing research on the Sri Lankan estuaries. According to co-authorship analysis, Japan, the USA, Australia, England, The Netherlands, Scotland, China, Belgium and Malaysia, are the leading countries to collaboration in the field of publications. The analysis shows that Sri Lanka is in the leading with 44 articles and 407 citations in the field. However, Japan (10 articles and 93 citations), USA (6 documents and 88 citations) are also the most important countries in the publication regarding Sri Lankan estuaries (Fig. 5). The co-operation and knowledge of the researchers of the above countries will be further strengthened for future estuary studies of Sri Lanka. These developed countries' teamwork have resulted in accurate research outputs through collaboration and knowledge sharing based on a wide range of research techniques. University of Kelaniya is the leading institution in the study of estuaries of Sri Lanka with 10 articles with 100 citations followed by University Ruhuna and NARA with 7 articles each. Although, some other Sri Lankan universities, the University of Moratuwa, University of Peradeniya, University of Colombo, Open University of Sri Lanka, and Uwa Wellassa University have also expressed interest in studies on Sri Lankan estuaries (Table 4). As a public sector entity, NARA is important in this regard. However, their publications have been more focused on the southern and western part of the estuaries in Sri Lanka (Fig. 10a), with only a few focusing on the eastern part of the country.

The use of keyword co-occurrence analysis was carried out in order to better identify the growing areas in Sri Lanka's estuary research. The top five most frequent keywords are “Sri Lanka”, “climate change”, “sediments”, “Negombo estuary”, “conservation” and “carbon” (Fig. 7a). From 2014 to 2016, researches were carried out that were primarily focused on keywords such as “meadows”, “mangroves” “salt water intrusion” “water quality” and “toc”, which were the subject of the studies undertaken. Despite this, the words acquired were seen from a variety of time periods based on the research situations they were observed (Fig. 7b). From 2019 to 2023, it was discovered that “climate change”, which is a significant concern in the contemporary period, as well as the consequences of “coast line change” “eutrophication”, ‘blue carbon” and “conservation” among other things, were the primary focus of study in the Sri Lankan estuaries during this time period.

Four clusters are revealed in the co-citation analysis of cited authors. The top three cited authors in the analysis were K.A.R.S. Perera, M.D. Amarasinghe, and L.P. Jeyatissa. The carbon removal and sequestration capacity of mangrove ecosystems in micro tidal estuaries was studied using several techniques in this core cluster. Co-citation analysis of cited sources

contains three clusters. The first cluster, led by Marine Geology, is made up of ten journals that are largely concerned with geology, botany and environmental management. The second cluster, led by Estuarine Coastal and Shelf Science, consists of 6 journals. In addition, the journal of Estuarine Coastal and Shelf Science was found to be the most cited among the cited sources, indicating that the majority of citations regarding Sri Lanka's estuaries were derived from this source. The most of publications in this cluster are concerned with marine and fish biology. However, the third cluster, led by Journal of Marine Pollution Bulletin, consists of 4 journals primarily focused on chemistry. Therefore, the findings of the articles evaluated for the study were categorized and elaborated under eleven main themes (Fig. 10b). The bar chart demonstrates that there has not been a uniform publication of articles about Sri Lankan estuaries according to their theme. Specifically, many articles are published on only a few of themes, yet very few articles exist on other significant topics.

Fig. 10a: The estuary related studies along the coastal stretch of Sri Lanka between 1987 and 2023.

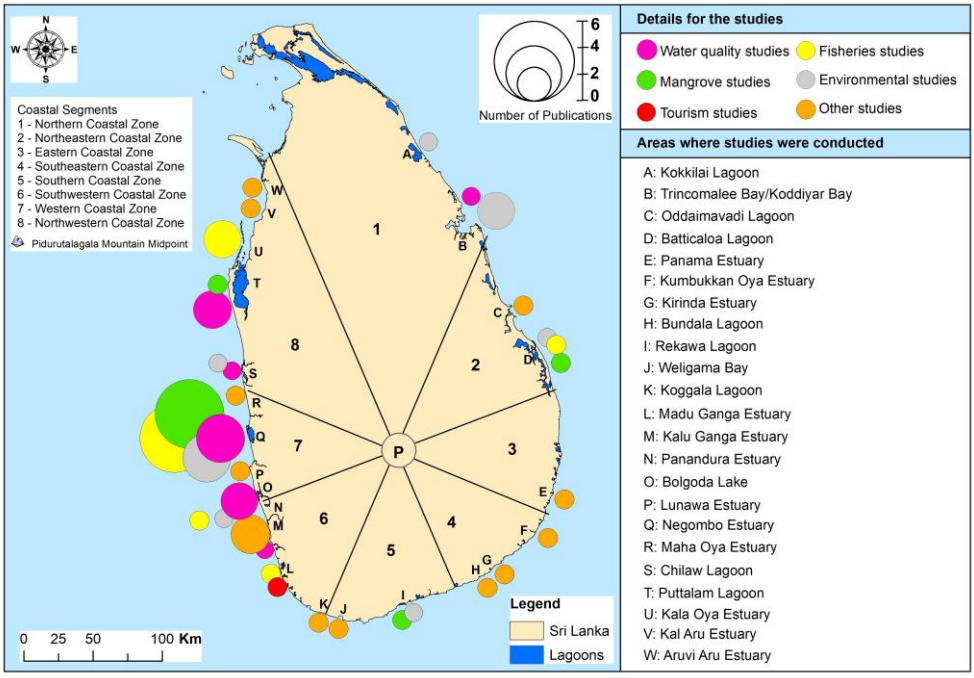
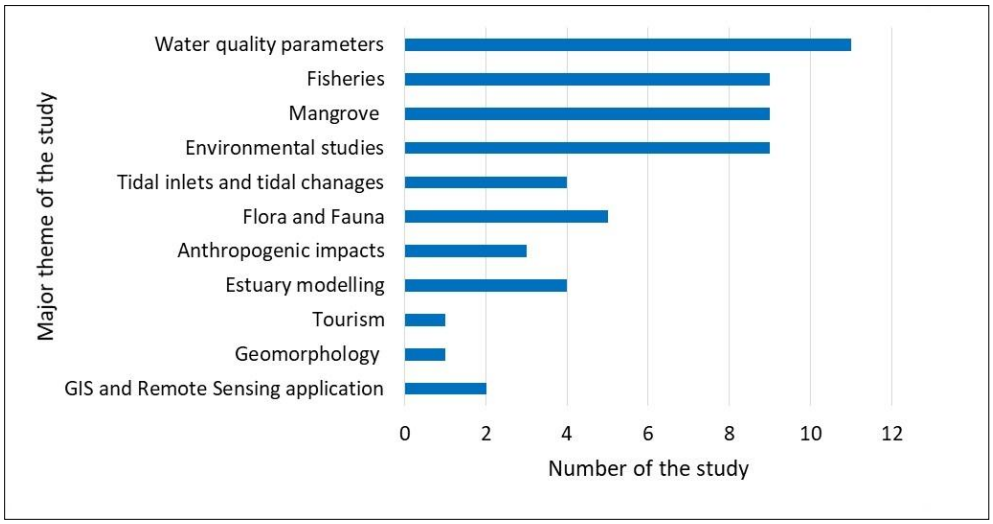


Fig. 10b: Major themes of studies undertaken in relation to estuaries in Sri Lanka.



Mangrove studies, water quality parameter surveys, and fishery productivity research have been conducted mainly in Sri Lankan estuaries. It was noted that publications on water quality studies (for examples: sediment composition, chloride contamination, chlorophyll monitoring, saltwater intrusion etc.) had been widely carried out. Studies on water quality have been conducted based on the seasonal sample collections and field observations that took part with the use of a hand held digital sounder and GPS receiver. Measurements of conductivity, pH, temperature, oxidation reduction potentials, and dissolved oxygen were taken with a water quality profiler as part of the analysis of the water quality parameters. In addition, study into the composition of the sediment in the estuaries was carried out, and X-ray fluorescence was used to analyse the results. It has been found that fisheries, mangroves and environmental related researches have been carried out equally. Theme of fisheries have focused the traditional fishing methods such as Jakothu, Kattudel and Brushpark, which occur near estuaries. The findings have been indicated that the above small-scale methods practiced on the southern and western coastal and its adjacent estuaries of Sri Lanka. The studies indicated that there were community-based management strategies in existence to manage fisheries activities.

In the mangrove study, carbon sequestration capacity of mangrove soil was analysed using wet oxidation method of chromic acid. Allometric relationships were used to quantify biomass in a study of atmospheric carbon removal capacity in mangrove ecosystems. To analyse the diversity of mangrove species, the Shannon-Wiener diversity index was calculated. Mangrove spatial distribution maps were created using ArcGIS's Inverse Distance Weighted (IDW) interpolation method. Mangroves in estuaries may sequester up to four times more carbon than terrestrial forests, which makes them an important tool for reducing greenhouse gas emissions. Their intricate relationship to the production of fisheries and the control of water quality displays their diverse ecological significance. Mangroves play an important role in maintaining the health of ecosystems by influencing water and soil quality in estuaries (Cissell *et al*., 2018), which in turn affects the growth and progress of mangrove forests. In addition, mangroves act as breeding areas and nurseries for a variety of terrestrial and marine organisms (Igulu *et al*., 2014). Considering their great importance, a lot of research probably concentrated on mangroves, fisheries output, and water quality studies

in the estuaries of Sri Lanka. Mangroves, fisheries productivity, and water quality evaluations in estuary environments have been the subject of many studies; nonetheless, it is critical to recognize the wider consequences of mangroves, particularly their importance to the tourism sector. Under the environmental studies for example: eutrophication and hypoxia, ecosystem services etc. had also been carried out. Flora and fauna, tidal changes and anthropogenic impacts studies have also been carried out to some extent in the estuaries.

Estuaries are ecologically significant transitional ecosystems that support high biological productivity, biodiversity, and essential ecosystem services. Several studies in Sri Lanka highlight that estuarine environments, particularly those associated with mangroves, serve as critical carbon sinks, contributing to climate regulation through carbon sequestration and blue carbon storage Perera & Amarasinghe, 2016a, 2019b; Suwandhahannadi *et al*., 2024). These systems also provide nursery and feeding grounds for a wide range of aquatic species, including fish and shellfish, as demonstrated in the Negombo estuary, where mangroves and seagrasses support diverse fish assemblages and fisheries productivity (Amarasinghe *et al*., 2002; Pinto & Punchihewa, 1996b). Furthermore, estuaries maintain ecological balance by regulating nutrient cycling, though excessive nutrient inputs can lead to eutrophication and hypoxia, thereby affecting ecosystem health (Hsieh *et al*., 2021). Mangrove ecosystems within estuaries also enhance sediment stability, support faunal diversity, and contribute to coastal protection (Arulnayagam *et al*., 2021; Phillips *et al*., 2017b). Overall, estuaries are vital ecological hubs that integrate physical, chemical, and biological processes, sustaining both biodiversity and human livelihoods.

Knowledge gaps and future research directions

Examining the current status of estuarine research in Sri Lanka, including published journal articles' trends, contributions, and significance, were the main goal of the study. Under these circumstances, the study's output was to attempt to identify essential research information gaps, and future prospective ways for the field. As part of this review of the literature, we have noted and recommended many approaches for overcoming such gaps.

- There are now several studies ongoing that concentrate on Sri Lanka's estuaries. However, many of the estuaries centred on the northern coastal zone are still not studied. The longest coastline in Sri Lanka is along the northern coast, while the second-largest coastal stretch is along the north-eastern coast. Moreover, there are numerous commercially important estuaries also located in this region. Nevertheless, the articles acquired for this study show that no exploratory work has occurred on Sri Lanka's northern shore. This situation has also been pointed out in some other studies (Arulnayagam *et al*., 2021; Madushika *et al*., 2022; Ragavan *et al.*, 2021). Therefore, it is necessary for the future scholars to study the estuaries to pay more attention to the northern and northeastern parts of Sri Lanka.
- The fact that the estuaries along the northern coast of Sri Lanka have been declared as high security zones (Soosai Siluvaithasan & Stokke, 2006) during periods of civil war was one of the reasons for the lack of studies focusing on the northern part of Sri Lanka. This situation will affect coastal development and long-term planning in the Northern Province. Even now, there are still a lot of high security zones and military camps adjacent to estuaries and lagoons in some places, particularly in the coastal districts of Mannar, Kilinochchi, Jaffna, and Mullaitivu. Researchers have found it challenging to conduct Light Detection and Ranging (LiDAR) surveys, use Unmanned Aerial Vehicle (UAV), and even do some specific field observations. As these estuarine areas are inaccessible by humans, applications with such spatial techniques are essential for their accurate monitoring. The situation was difficult for

scholars to do field study in such locations, which may be one of the reasons that no studies have been published. This has resulted in significant research and knowledge gaps on North and North-Eastern coastal sectors of Sri Lanka (Thasarathan *et al*., 2024; Warnasuriya *et al*., 2018). Therefore, it is necessary for the responsible departments to take steps to equip the researchers to conduct independent studies.

- There is a significant need for more comprehensive study of estuaries in particular theme. There is an essential necessity for estuary and its geological and geographical researches. The study regarding the geomorphic changes of the estuary ecosystem due to siltation is very important for the future paleo-geomorphological studies on estuaries. The study output showed that no geomorphological researches, such as detailed estuary landform or land unit identifications and its mapping, temporal changes related studies carried out using GIS and Remote sensing techniques. Although the results of this study show that many studies have been done in the Negombo estuary area, some studies have indicated that even in that estuary, more attention should be paid to geomorphological studies (Dahanayaka, 2023). The contemporary situation highlights the gaps for future researchers to increase their research on the morphological changes of the estuaries and the detailed studies of its geomorphic landforms.
- Sea level rise has detrimental effects on areas along the shore, including erosion and the destruction of coastal ecosystems including mangroves and tidal flats in the estuaries (Hossen & Sultana, 2023; Thasarathan *et al*., 2024). Sea levels are expected to rise by 0.1 to 0.2 m over the period of the next 50 years, resulting in an inundation that will reach less than 1.8 m inland from the current sea level. Furthermore, it is anticipated that during the next 200 years, sea levels would rise by about 0.7 m, submerging land by 3.5 −15.0 m above the present sea level (Palamakumbure *et al*., 2020; Thasarathan *et al*., 2024). Therefore, it is necessary to carry out systematic studies continuously in Sri Lanka to focus on these issues in regional level. As a result, preparedness researches on the possible effects on coastal estuaries and their future conservation must also be done.
- Cyclones and tsunamis in the Bay of Bengal can strike Sri Lanka's northeast and south coasts at any time. However, no studies with detailed information on the changes in estuarine ecosystems observed in the north-eastern regions as a result of the tsunami disaster have been conducted thus far, becoming a challenge for future preparedness. Despite this, since most of mangrove studies were published in local journals, only a few worldwide scholars who concentrate in mangroves were attracted (Arulnayagam *et al*., 2021; Suwandhahannadi *et al*., 2023).
- There are a few studies that focuses solely on Sri Lankan estuaries and tourism. Estuaries and lagoons around Sri Lanka's coastline have an inherent capacity for coastal tourism and eco-tourism potentials, however, there have only been a very limited number of studies that emphasize this. Therefore, future interpretive researchers must publish significant work in this field. Hence it is necessary to conduct studies with integrated and multidisciplinary approach.

Therefore, future researchers must give it more attention, but the publications that have already been published are greatly helpful. There are not sufficient additional studies that have been published, but the studies that are available are noteworthy for employing

important research techniques to ascertain the necessary follow-up study based on these findings. Thus, these issues must be the main focus of future research.

CONCLUSION

The current study endeavoured to quantify the amount of scientific research and its scopes that were done in WoS on Sri Lankan estuaries between 1987 and 2023. This study analyzed 58 papers and provided a comprehensive review of the most important studies on Sri Lanka's estuaries. The research found that while scholarly articles about Sri Lankan estuaries were generally published in WoS, the number of yearly publications did not increase over time. It has been shown that although fewer articles are published, they are considered high-quality. This article provides an in-depth summary of the most influential papers on estuary studies, along with recommendations for further research, despite some limitations. The data was gathered specifically from the WoS core collection using selected keywords. As the keywords were in English, the study may have been affected by language bias. Local and scientific articles obtained from other sources may also be restricted. The number of citations and publications may vary slightly depending on when the data was collected. These limits indicate the need to broaden research, particularly by examining different languages and literary sources.

The research has conceptual significance because it addresses the needs of future estuary studies in Sri Lanka. Researchers will gain a more comprehensive understanding of the literature on Sri Lanka's estuaries, including emerging research trends, significant studies, and international collaboration. The fact that some studies have been conducted in international collaborations and have produced a wealth of technical outputs is encouraging. Previous studies have indicated that Sri Lanka's estuaries have influenced the country's fisheries, water quality, mangrove coastal biodiversity, and nature-based tourism. However, there are gaps in certain aspects of coastal estuaries in the future, such as landforms/land unit studies, detailed land system mapping, and estuaries and their shoreline changes, because there has been no continuous research on these topics. Low-lying estuaries are increasingly under threat due to increased global warming. Therefore, the above kind of research is very important for the future coastal conservation and predictions in Sri Lanka. In order to monitor and conserve future coastal resources, it is necessary to perform continuous long-term research in estuaries and their adjacent areas. Geo-informatics techniques are deemed vital for predicting the impacts of coastline change, the richness of estuarine diversity, and human activities near estuaries. Therefore, future research scholars have to concentrate on such spatial techniques. Widespread study across a nation's estuaries is necessary; otherwise, there will be significant gaps in the availability of research in these and related fields. Future estuary studies should adopt multidisciplinary, holistic ecosystem approaches. Despite these findings, they imply that tourism and geomorphologically related studies on estuaries are needed and should also be further linked with geo-informatics approaches to monitor the spatial and temporal changes. Therefore, further research are needed to prove the requirement for integrated network management for estuary monitoring. Publication cost may be a reason for fewer number of articles and for limited published manuscripts in recognized databases (e.g., WoS) from Sri Lanka. However, the quantity of citations may increase with time. To filter out extraneous material and capture a broader center of Sri Lankan estuary-related studies literature, a more comprehensive thematic and content analysis is required.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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